Overview of The Palomar Testbed Interferometer

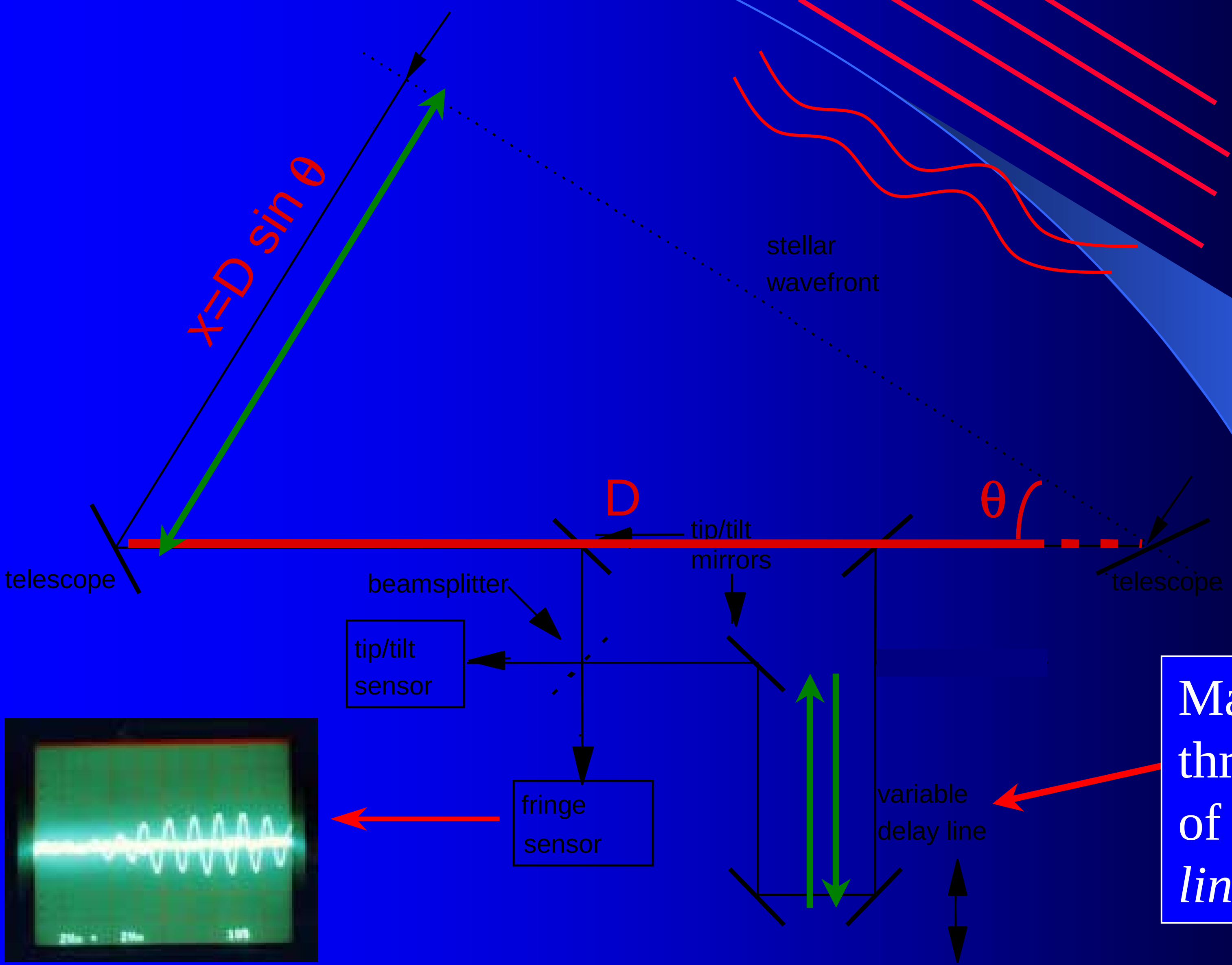
David Ciardi 2002 Interferometry Summer School

Outline

- Brief Overview of two-element interferometer
- Tour of PTI
- Understanding visibilities
- PTI & Scientific Applications

Two-Element Interferometer

Star is at infinity

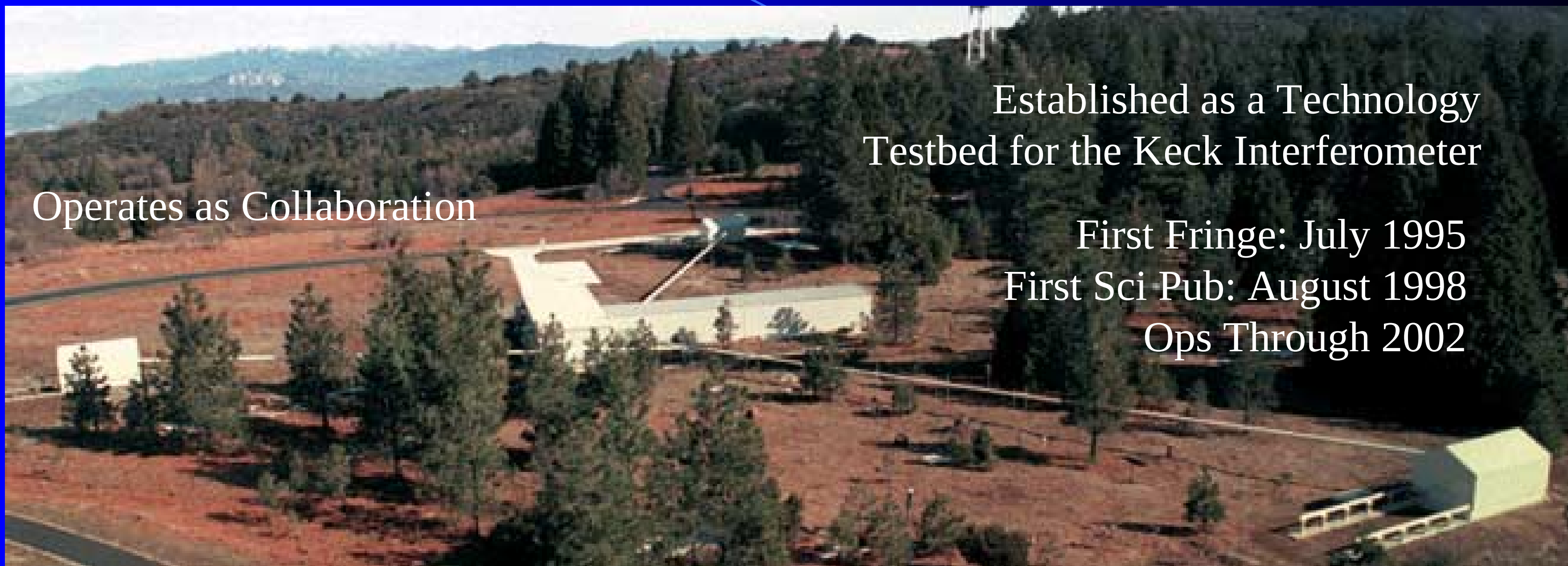


Match paths through use of *delay lines*

Palomar Testbed Interferometer (PTI)

PTI Vital Statistics

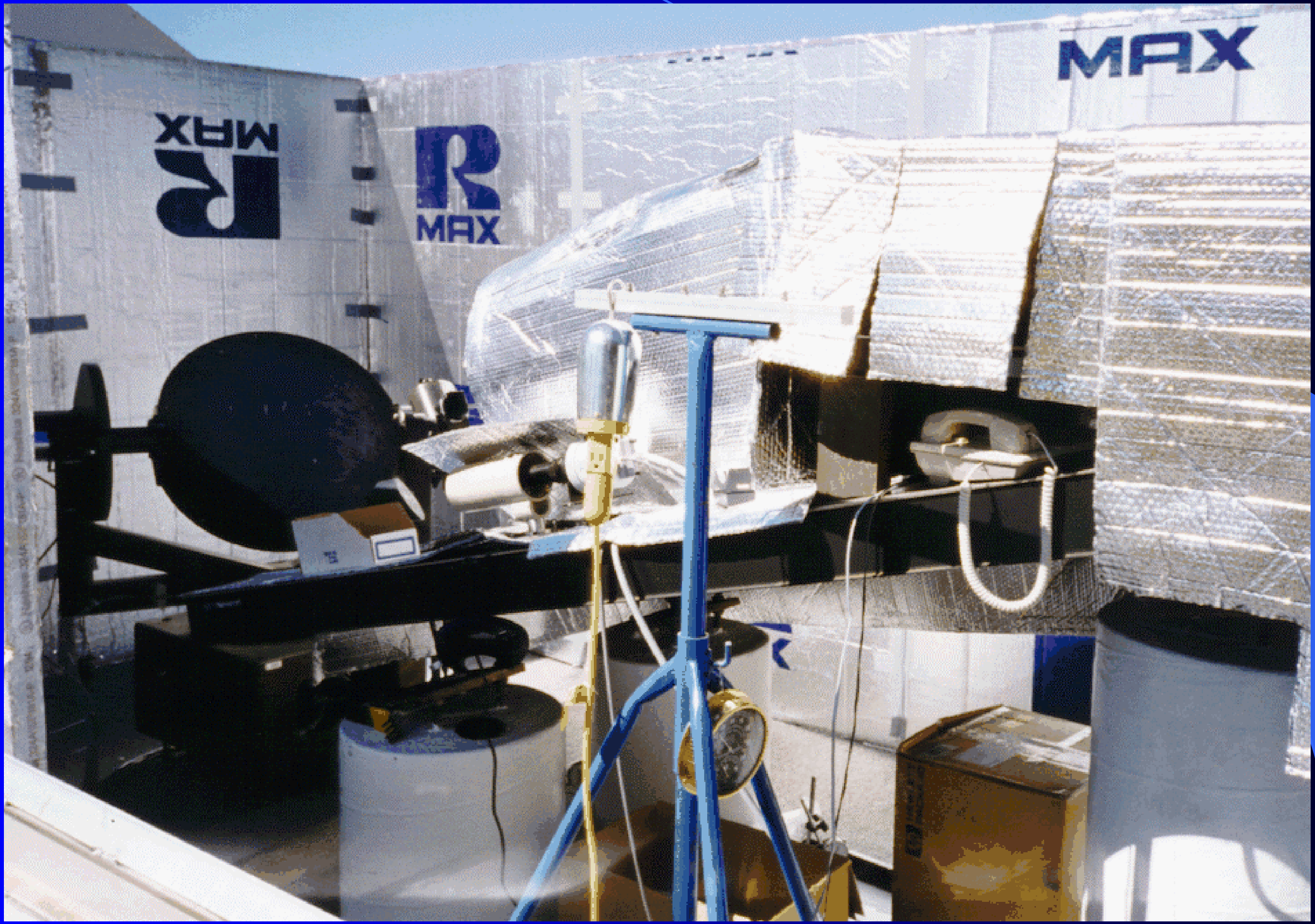
http://huey.jpl.nasa.gov/palomar



- PTI is a Near-IR single-baseline interferometer
  - 40 cm Sidereostats, NS (110 m) and NW (85 m) baseline combination
  - 1" FOV, 1-100 mas size sensitivity
  - 1.65 μm & 2.2 μm - Five Spectral Channels (R~20)
  - Limiting Mag K ~ 6, V~10

PTI Photo Tour

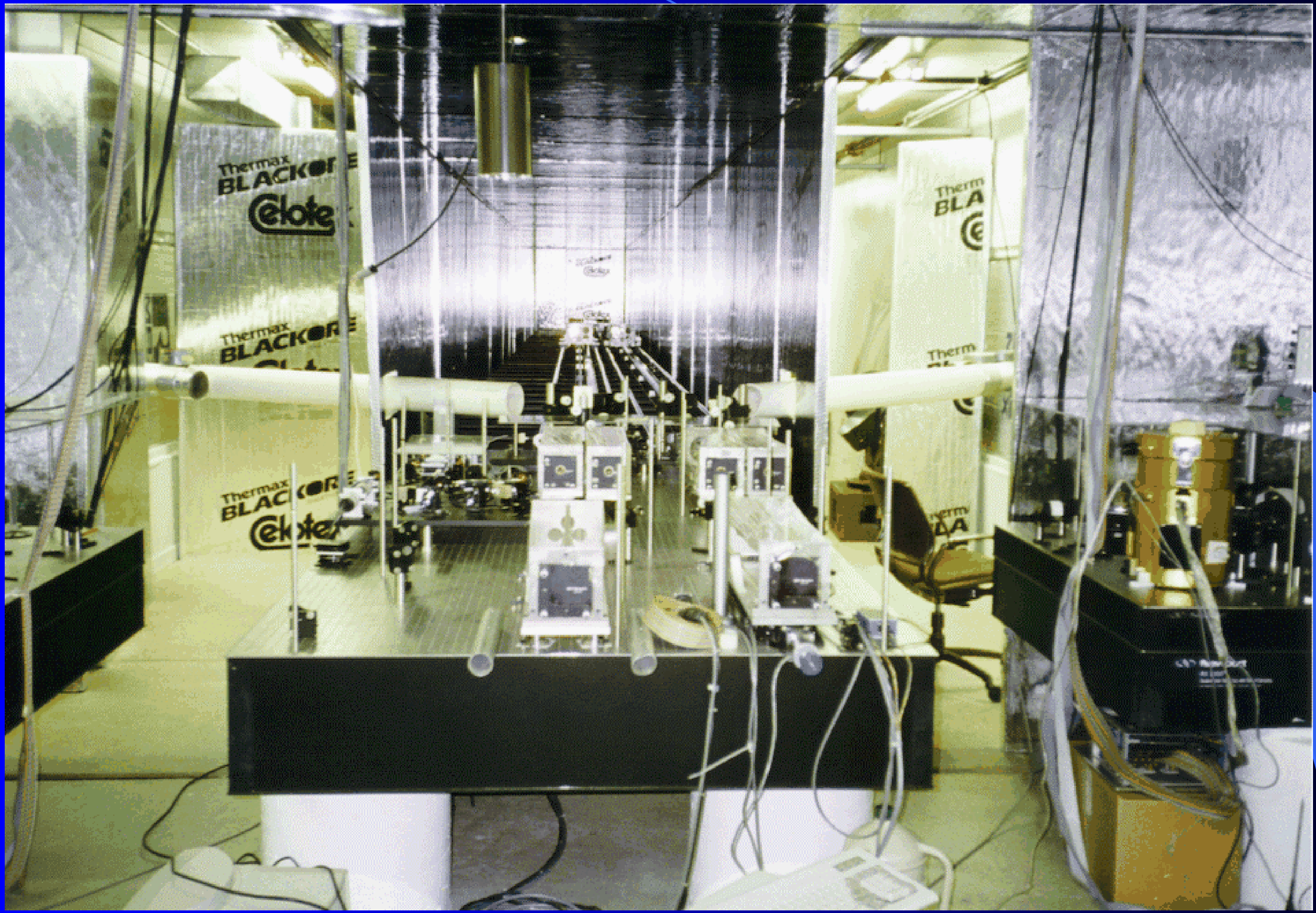
PTI Siderostats



PTI Siderostats

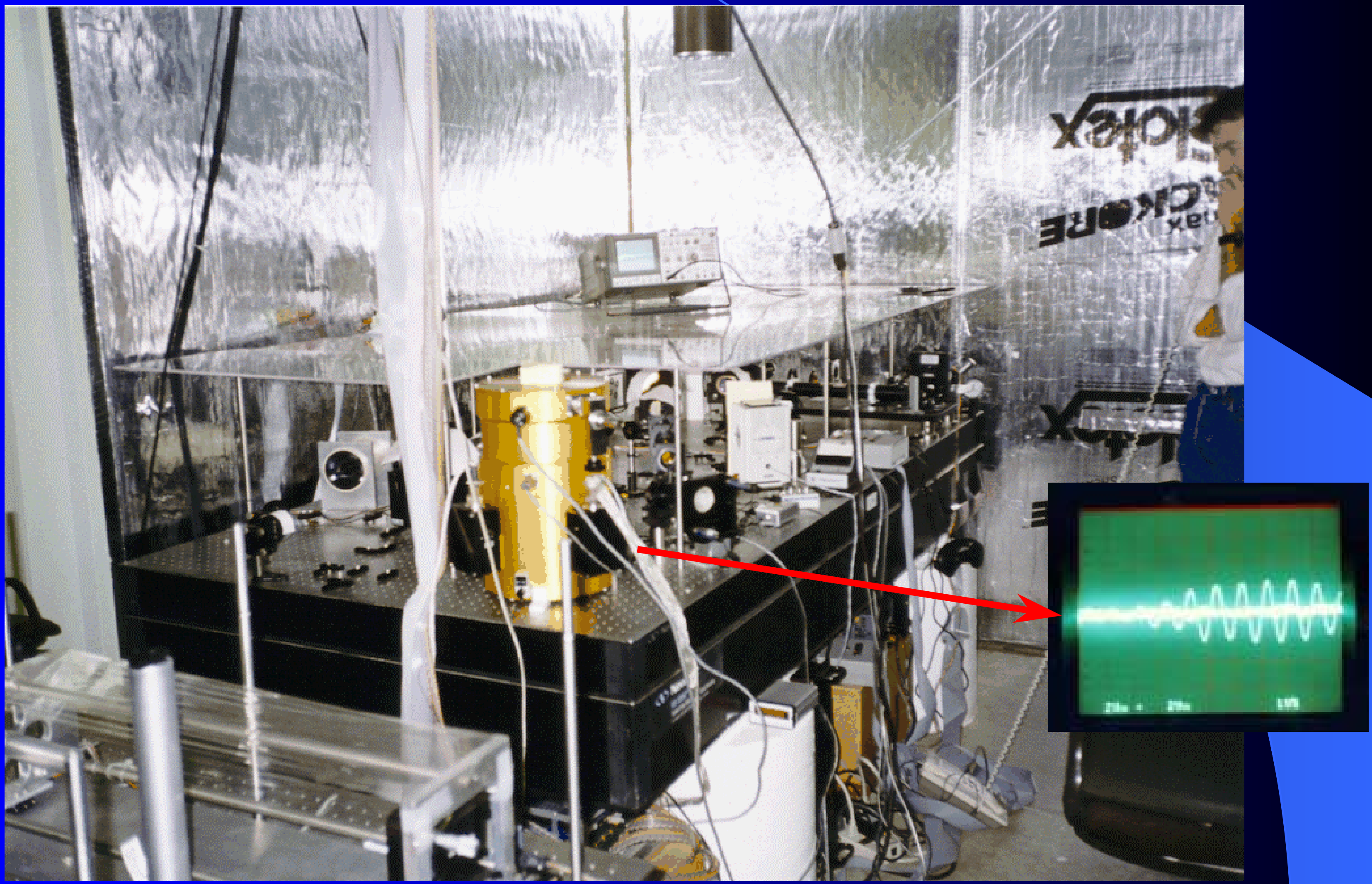
PTI Vacuum Tubes

PTI Delay Lines

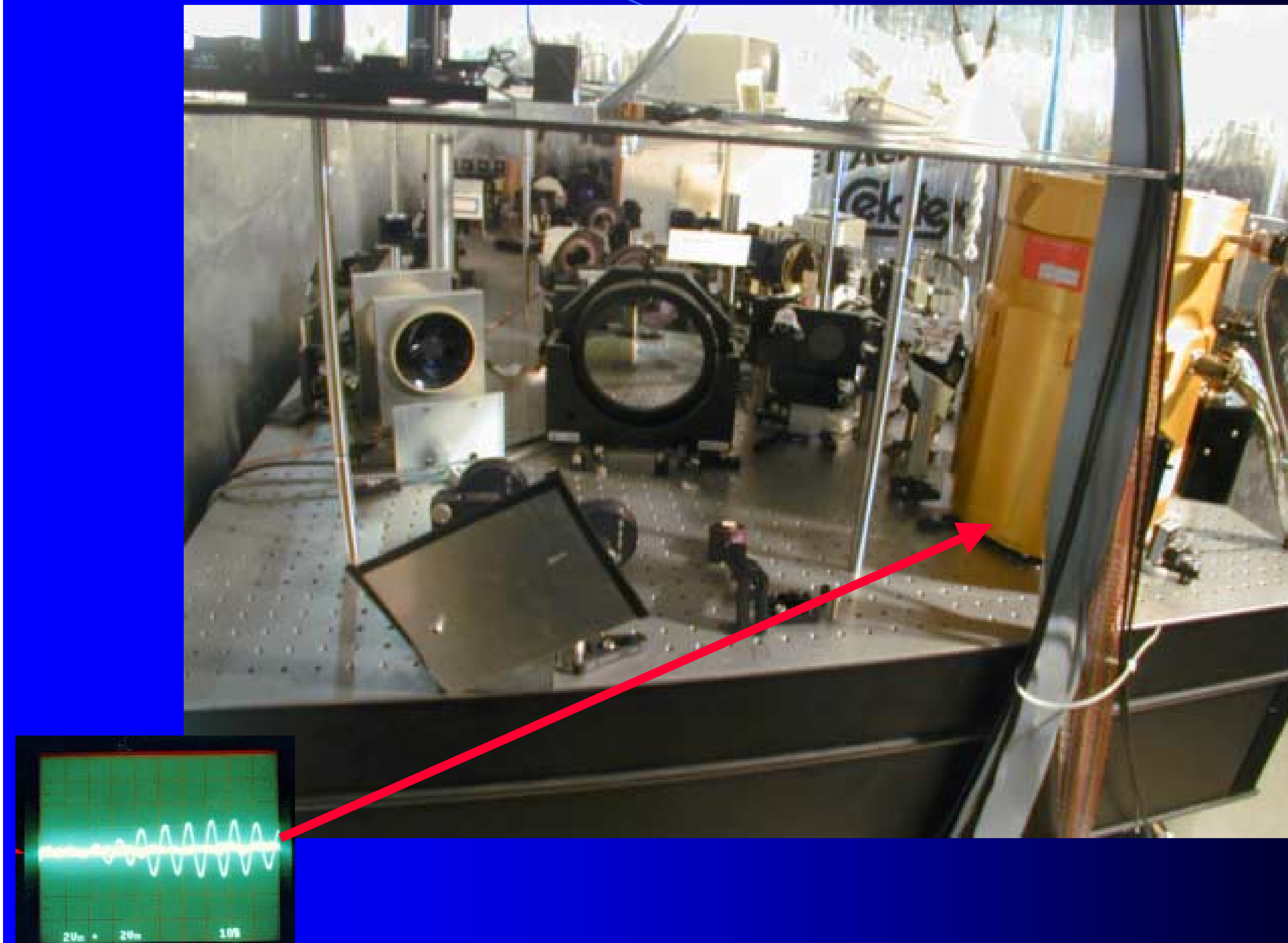


PTI Delay Lines

PTI Primary Recombination Table



PTI Beam Combination Table

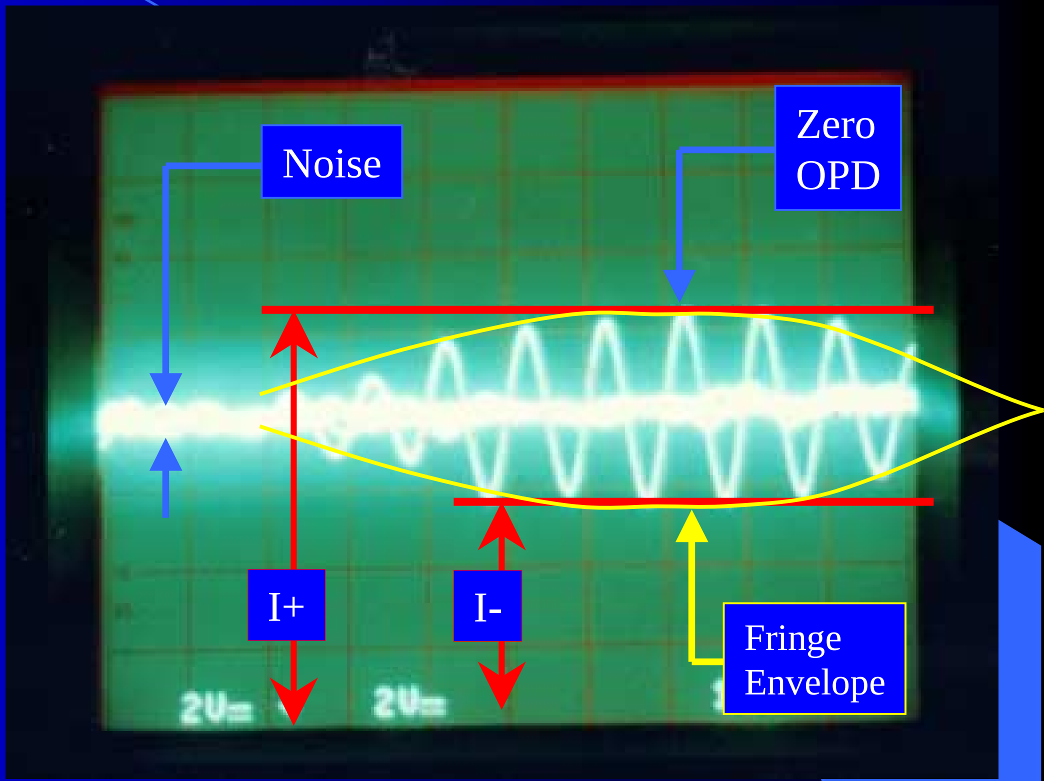


Fringe Visibility

- Constructive & destructive interference of light
- Fringe contrast or visibility:

$$V = \frac{I^{+} - I^{-}}{I^{+} + I^{-}}$$

- Calibration issues
  - Detector linearity
  - Zero point measurement
  - Noise characterization
- Coherence Time of Atmosphere: ~10 ms



Actual starlight fringes from IOTA - β And
Photo credit: R.R. Thompson

Visibility Functions

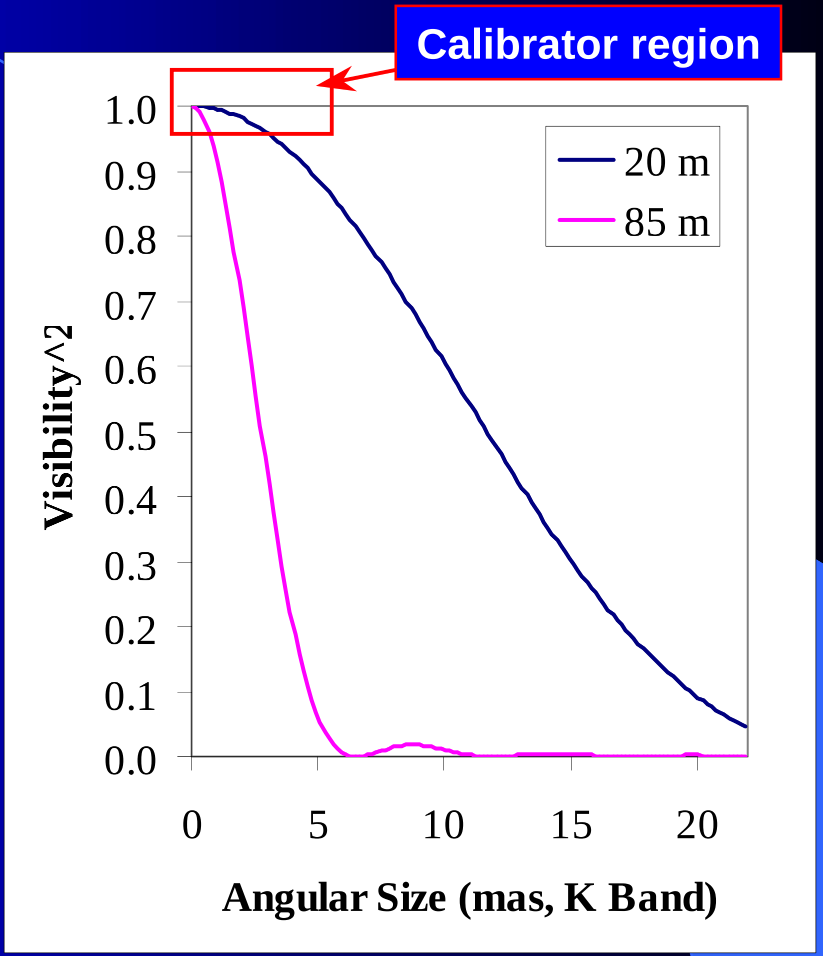
- Need to convert the measured visibilities or fringe contrasts into something meaningful ….
- Visibility is measure of the intensity of the light fringes at a location in the *u,v* plane
- *u,v* plane ⟷ *Fourier Transform* ⟷ *image* plane
- Sampling in *u,v* plane depends on
  – source location
  – telescope location/orientation
  – hour angle coverage
- *Because not a filled aperture, incomplete sampling in u,v plane*
- *Loss of phase information at PTI*

Typical Observing Program

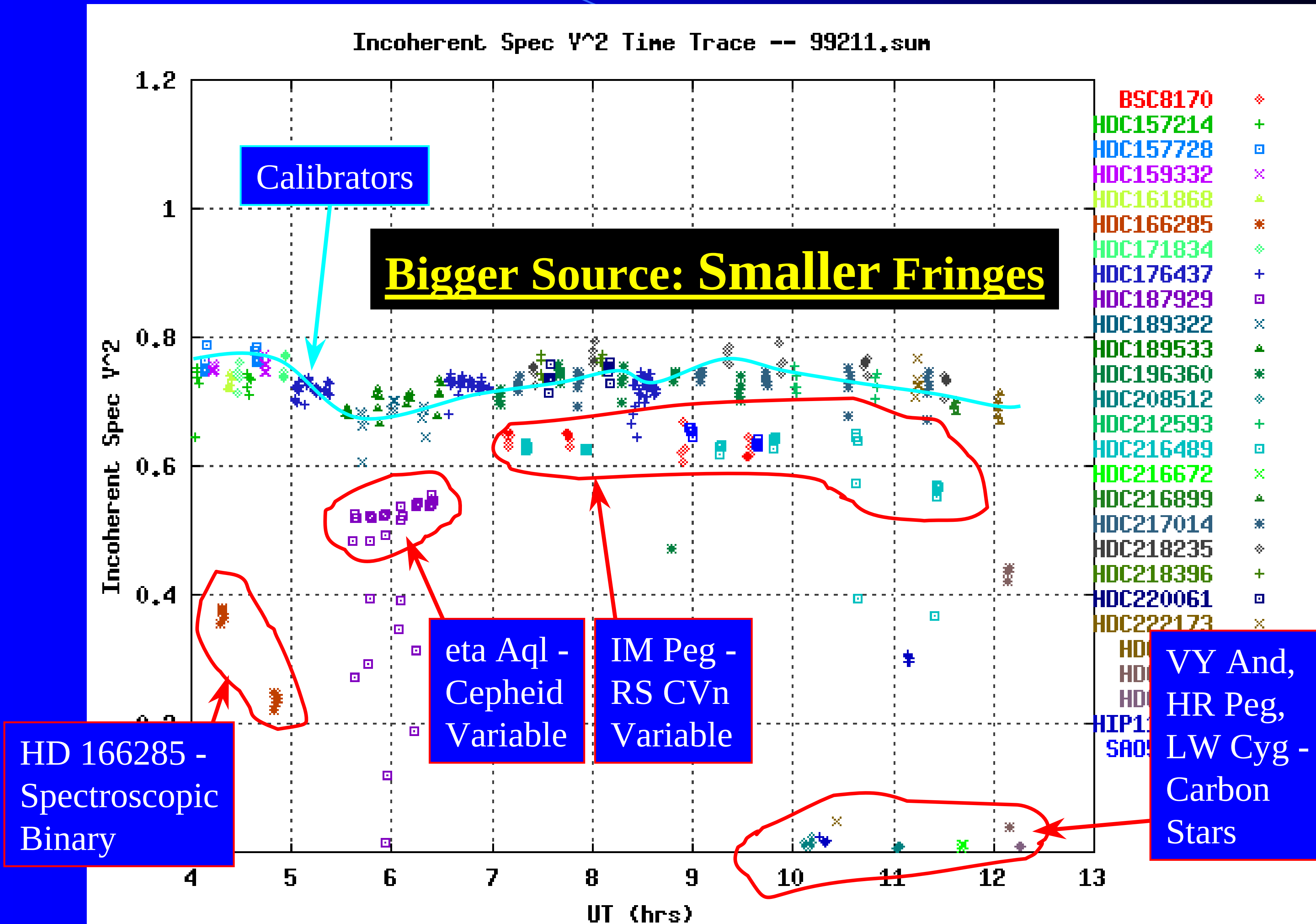
- Calibration star (‘calibrator’) - target - calibrator
  - Bracket the target with unresolved sources
  - Time dependence of atmosphere, instrument
- Evolving targets
  - Can appear change with baseline projection, time, wavelength
  - Calibrator - target - calibrator - resolved calibrator
    - Choose a secondary resolved object not expected to evolve

Visibility Function: Calibrators

- Atmospheric and instrumental effects reduce system V^2
- Observe 'unresolved' sources to establish system response
  - Use an estimate of size
  - Assume V^2 gains are equal
  - Flattening portion of visibility function $\rightarrow$ errors in calibrator size do not translate into errors in system V^2
- PTI Unresolved Calibrators <0.7 mas



PTI Visibility Data



What's the Big Deal?

- V^2 data by itself is not terribly useful information
- Through the use of ancillary data and models, it is enormously powerful
  - Interferometrists need to make lots of single-dish friends
  - Or be fully paid up on their journal subscriptions

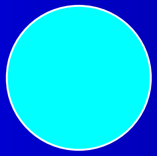
Science with PTI

22 Refereed Journal Articles since 1998

Single Stars:

- For a “uniform disk” visibility matches:

$$V = \frac{J_1(x)}{x} \qquad x = \frac{\pi\theta B}{\lambda}$$

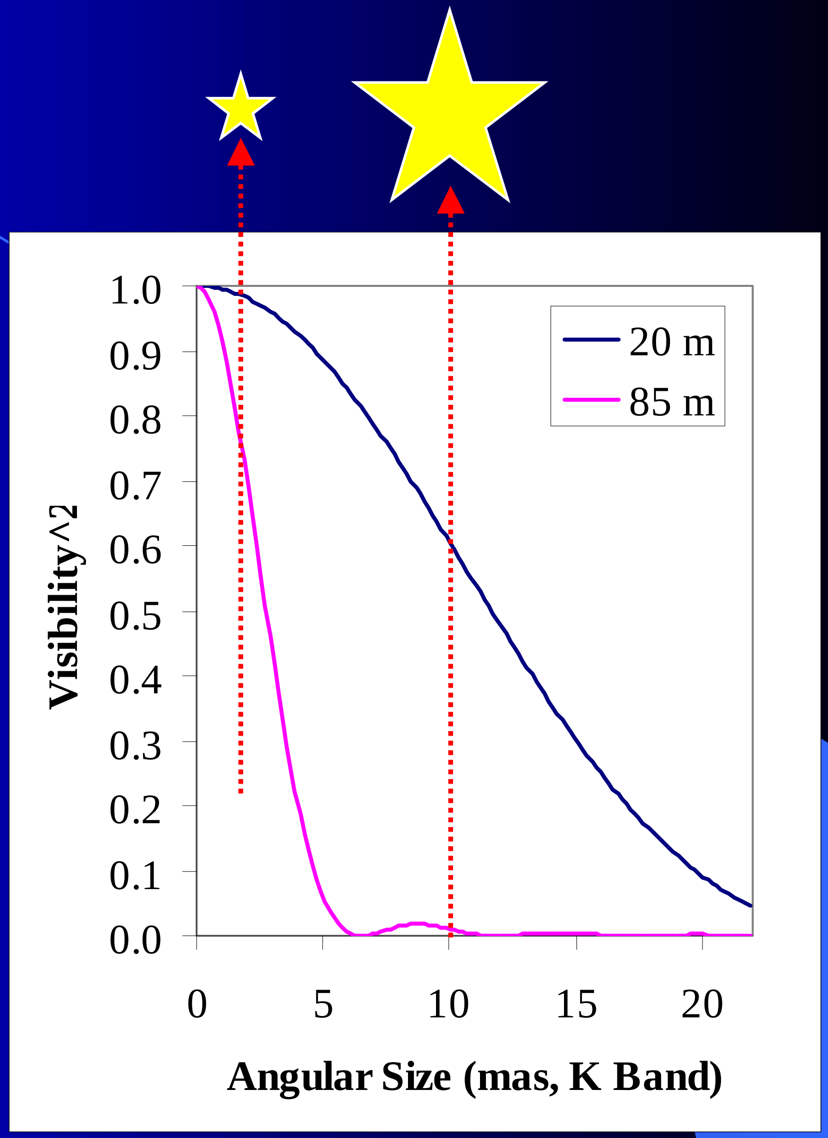


  B is the projected baseline

  θ is the stellar disk size

  λ is the wavelength

- Baseline, wavelength known
- Solve for stellar angular diameter θ



Single Stars: Basic Parameters from Angular Diameters (θ)

- *Direct observation* of fundamental stellar parameters
- Effective temperature is defined as: $L = 4\pi\sigma R^2 T_{\mathrm{EFF}}{}^4$,

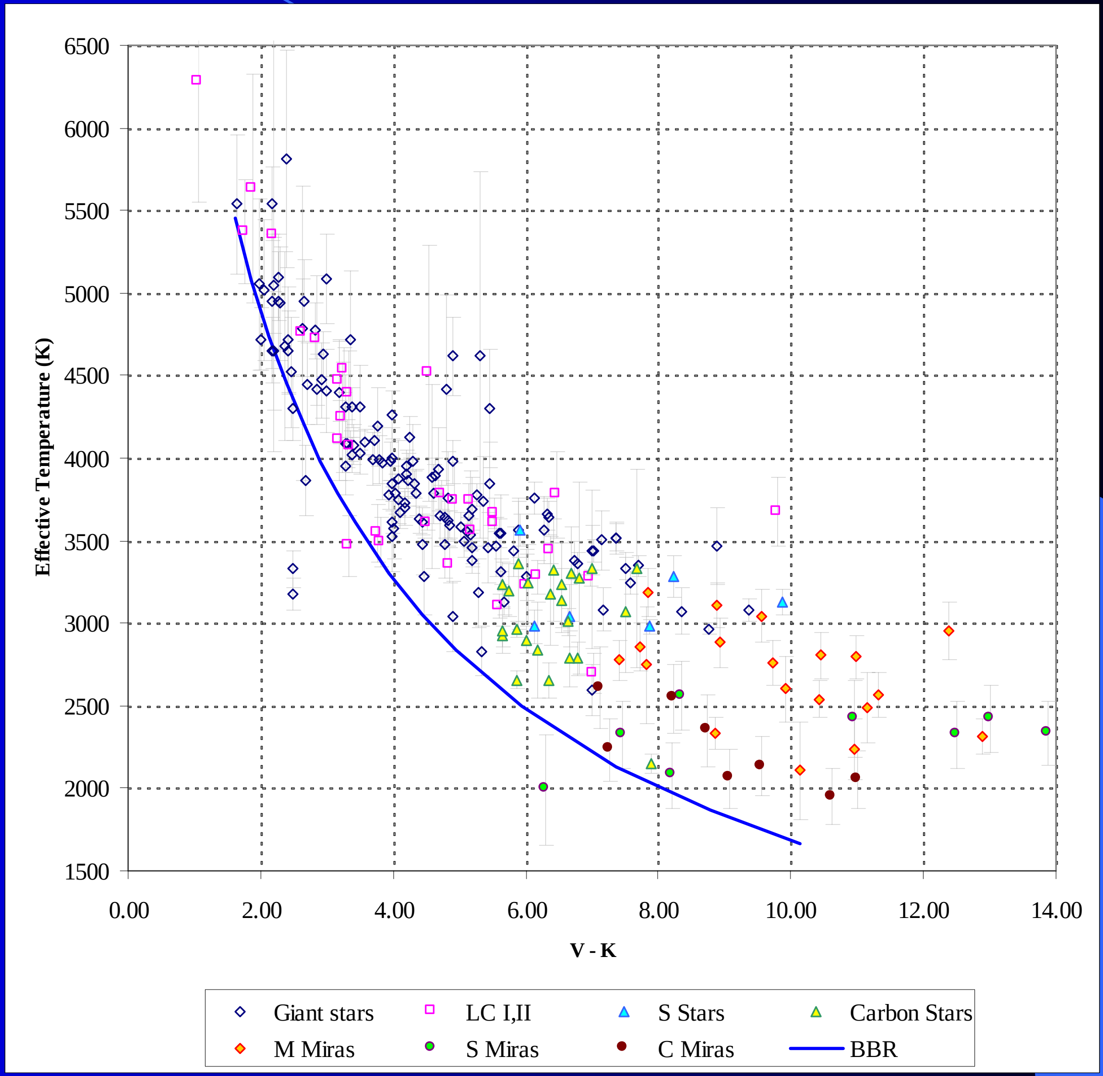
  which can be rewritten as: $T_{\mathrm{EFF}} = 1.316\times10^7 \left(\frac{F_{\mathrm{BOL}}}{\theta_{\mathrm{R}}^2}\right)^{1/4}$

  – F_{BOL} is the bolometric flux (W cm^{-2}), θ_{R} is the Rosseland mean stellar angular diameter (mas)
- Linear radius is simply:
  – Hipparcos (Perryman et al. 1997) distances now available
  – Uncertainties in parallax (typically ~15-20%) still largest contribution to error

$$R = \tfrac{1}{2}\theta \times d$$

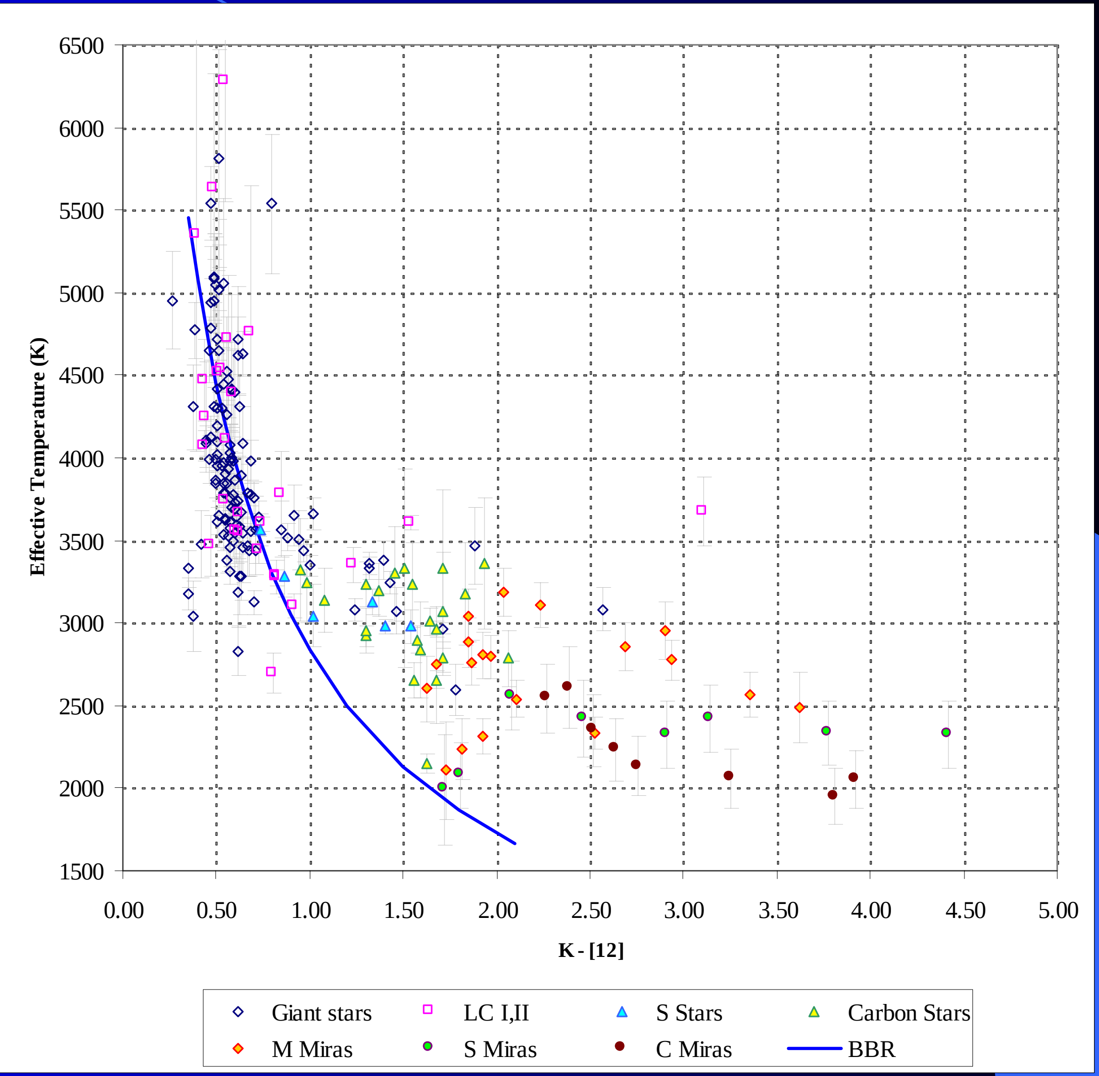
Evolved Stars: Effective Temperature vs. V-K Color

- Blue: Blackbody behavior
- Indications of increased absorption bands at V at low T_{EFF} (Barbuy *et al.* 1992, Jørgensen 1994)
- Clear separation of the abundance subtypes into regions on the plot
- PTI/IOTA data



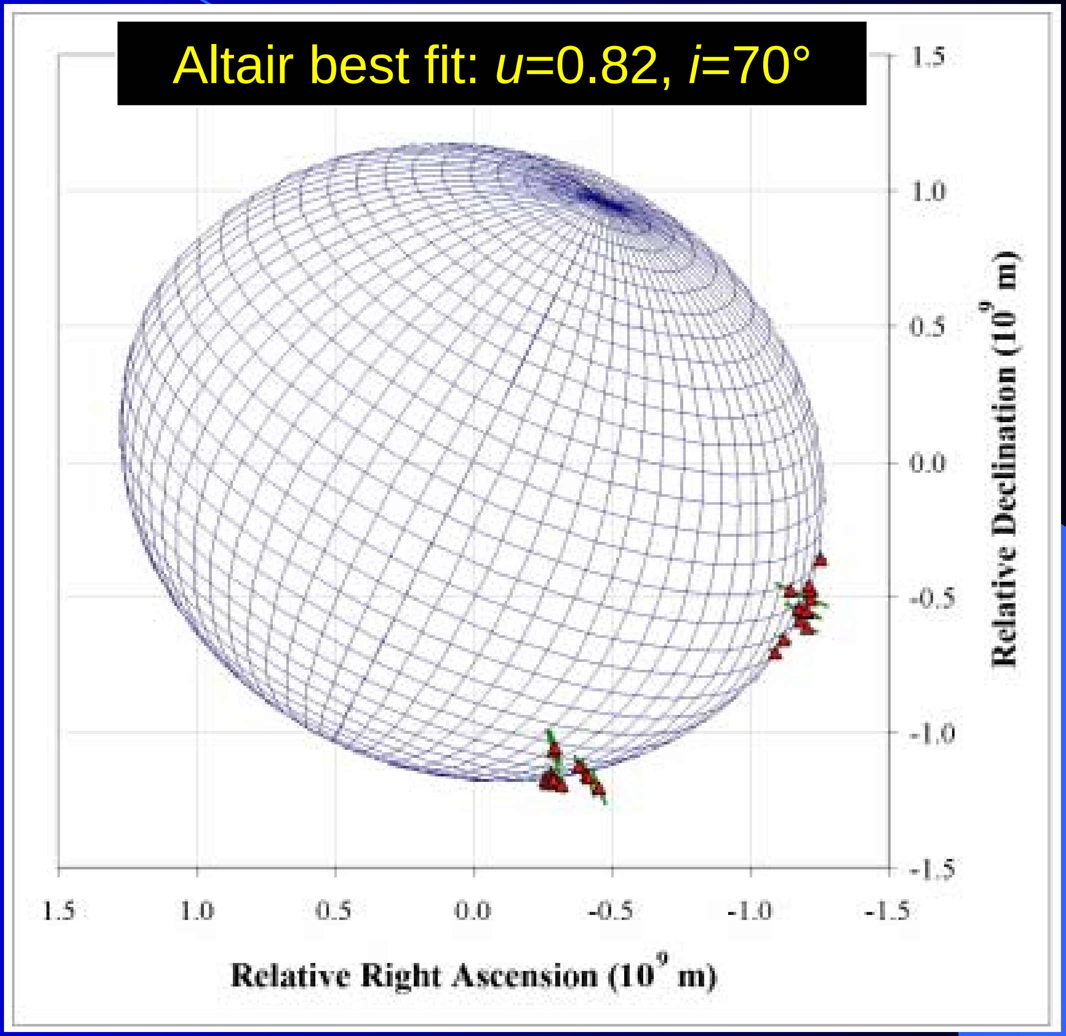
Evolved Stars: Effective Temperature vs. K-[12] Color

- K-[12] reasonable indicator of dusty mass loss
- Blue: Blackbody behavior
- Substantial departure from BBR curve at K-[12] ~ 0.80 by Miras, carbon stars
- Indication of onset of mass loss (Le Sidander & Le Bertre 1996, Beichman *et al.* 1990) for the more evolved stars
- PTI/IOTA data



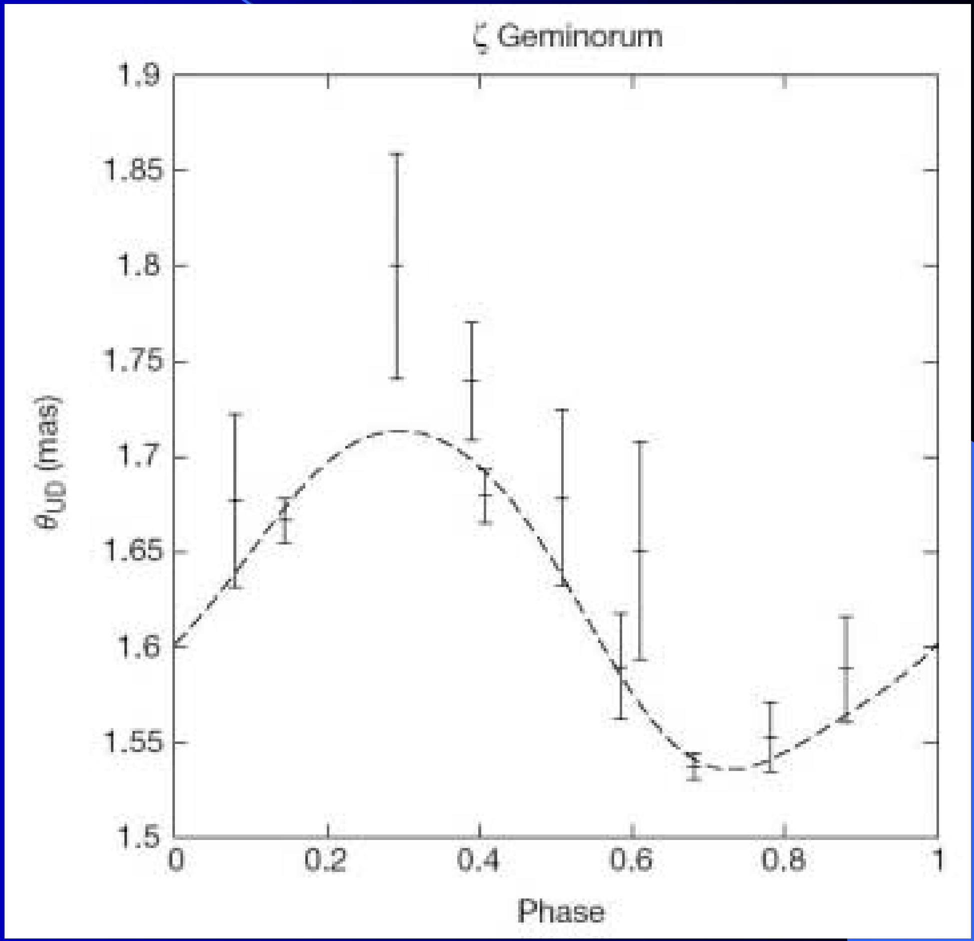
Single Stars II: Rotational Velocity

- Altair observed with NS and NW baselines.
- Yield different V^2 measurements
- Unique solution for $v \sin i$ = 210±12 km/s
- Altair 10h rotation!



Single Stars III: Cepheids

- First Direct measurement of radial size changes of cepheid variable.



Binary Star Systems

- Two point sources

$$V(s) = \left[P_0 + (1 - P_0)\cos^2(\pi s r)\right]^{1/2}$$

$$P_0 = \left(\frac{B_1 - B_2}{B_1 + B_2}\right)^2$$

- B1 & B2 brightness of sources.
- r = binary separation
- s = baseline/wavelength

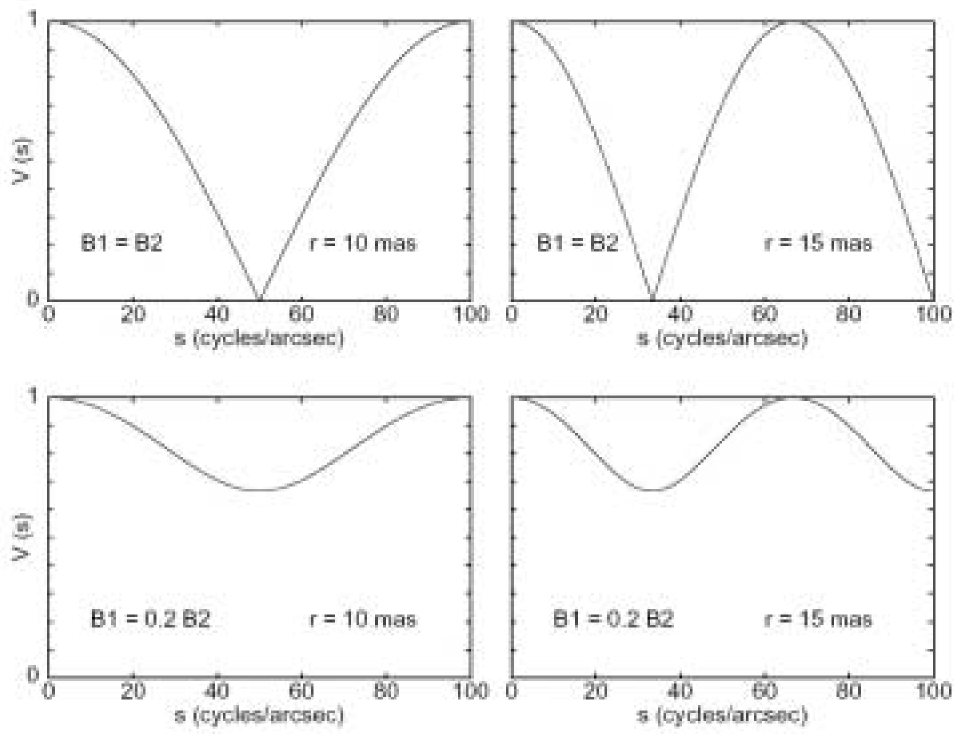
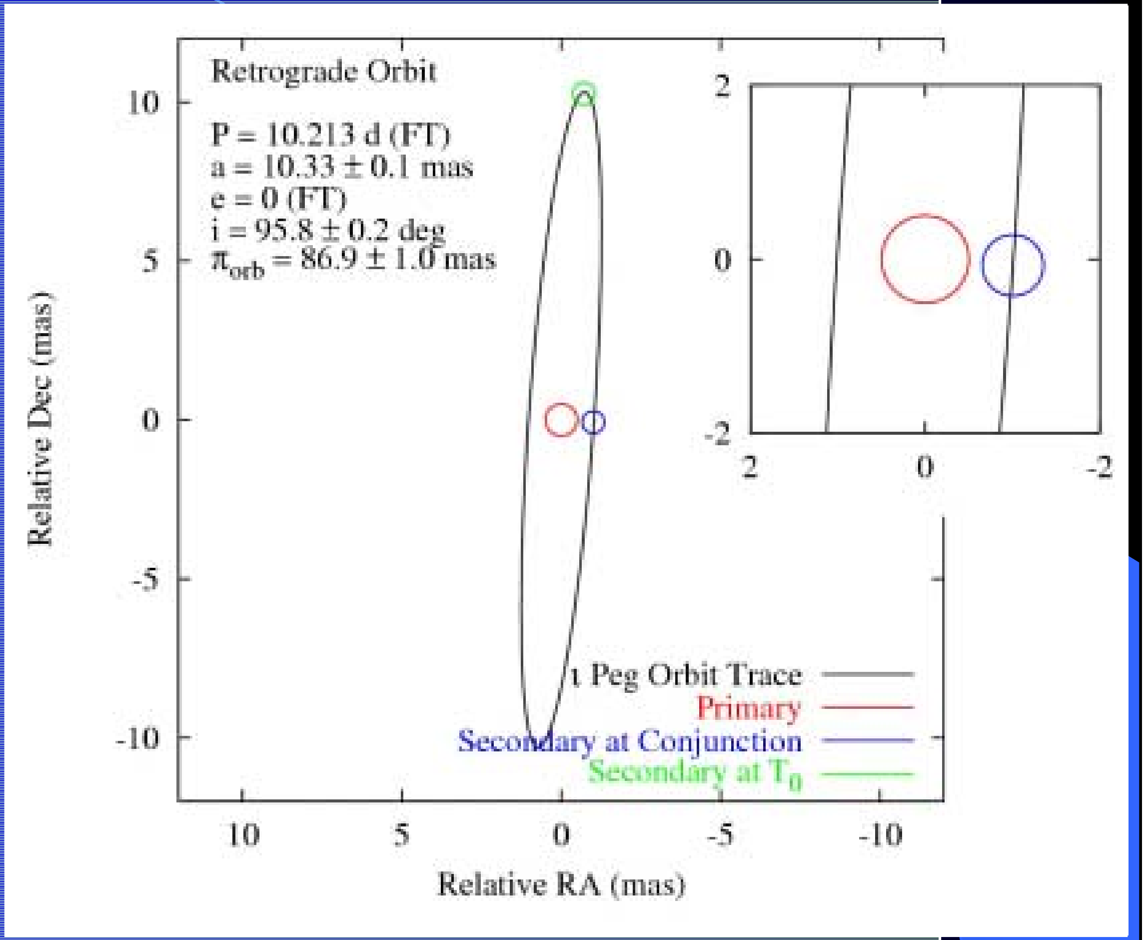


Figure 12.7: Double-star visibility curves. Note how the position and depth of the minima change with separation and brightness ratio, respectively.

ι Pegasi

One HST WFPC 2 Pixel

- Well-known binary system
- Established as a SB2 by Fekel and Tomkin who inferred the "possibility of eclipses" (1983)
- Average Absolute V^2 Residual 1.4% Over 114 Scans
- Precision photometry : no eclipses (Boden *et al.* 1998 *ApJ*)



Circumstellar Material

- Circumstellar Disk: measured visibility is resultant of Stellar Disk + Circumstellar Disk

- Simplest Case:
  - Unresolved Star
  - Uniform Circumstellar Disk
- *Vp* = flux ratio between star and disk
- *a* = size of disk

- No reason star needs to be unresolved …

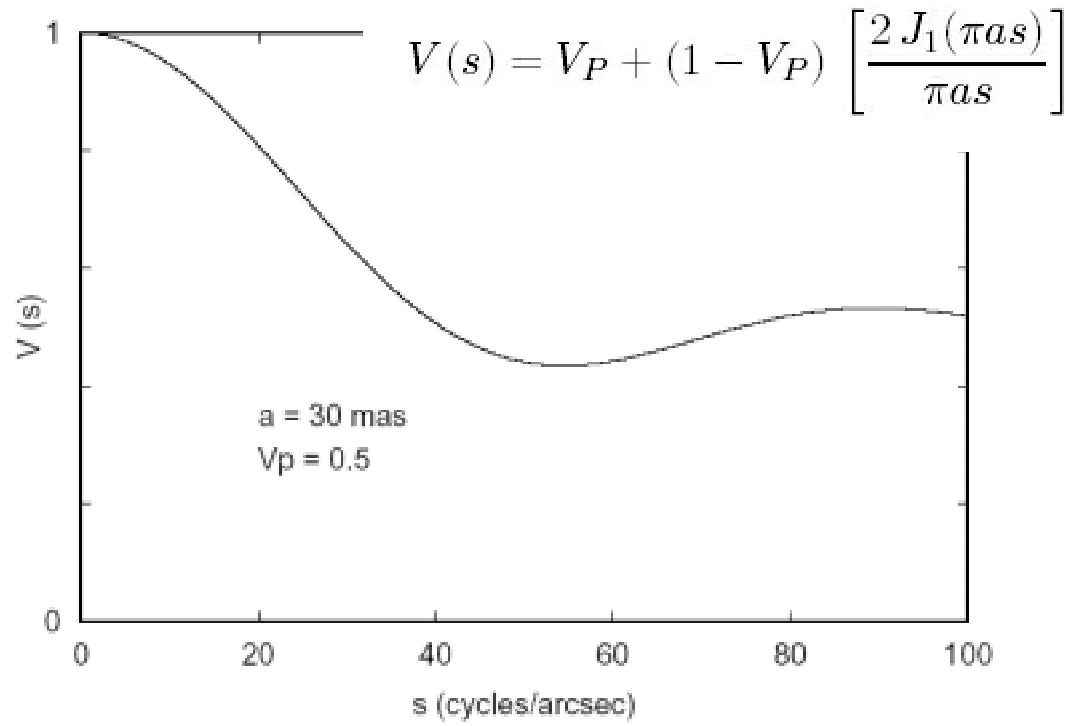
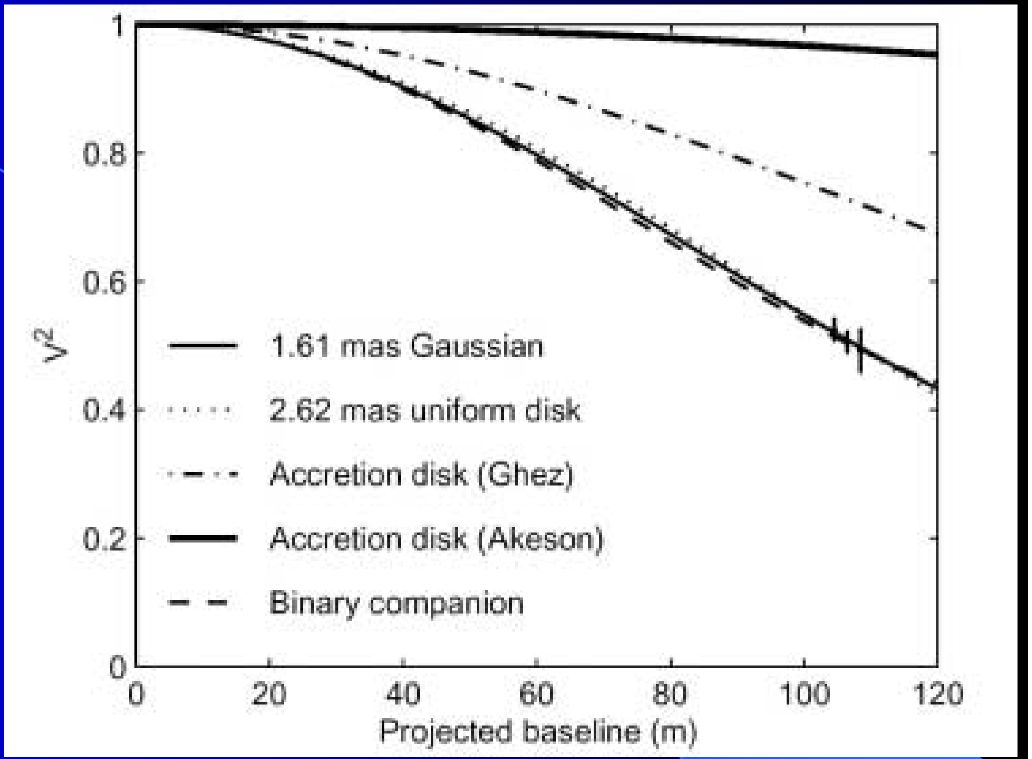


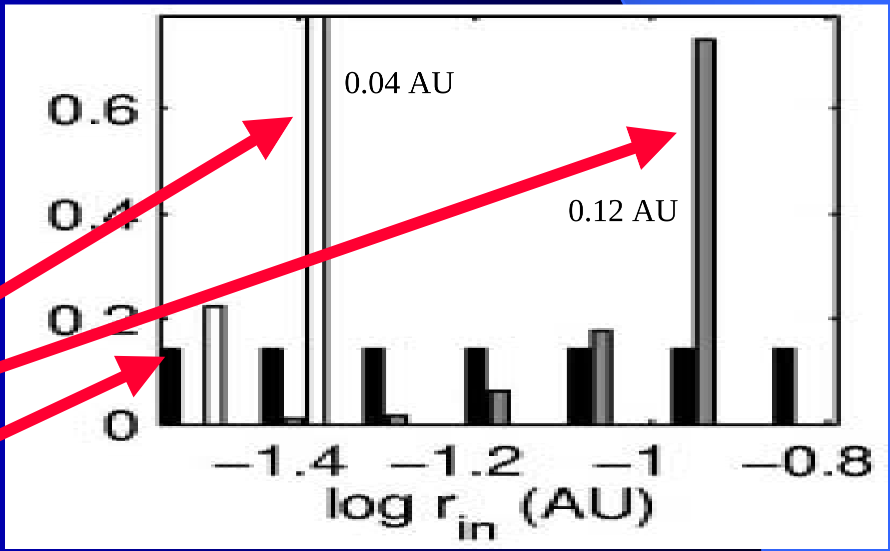
Figure 12.9: The visibility curve for a uniform-disk surrounding a point. The disk size is 30 mas and there is 50% in each of the two components.

Circumstellar Material I: YSOs

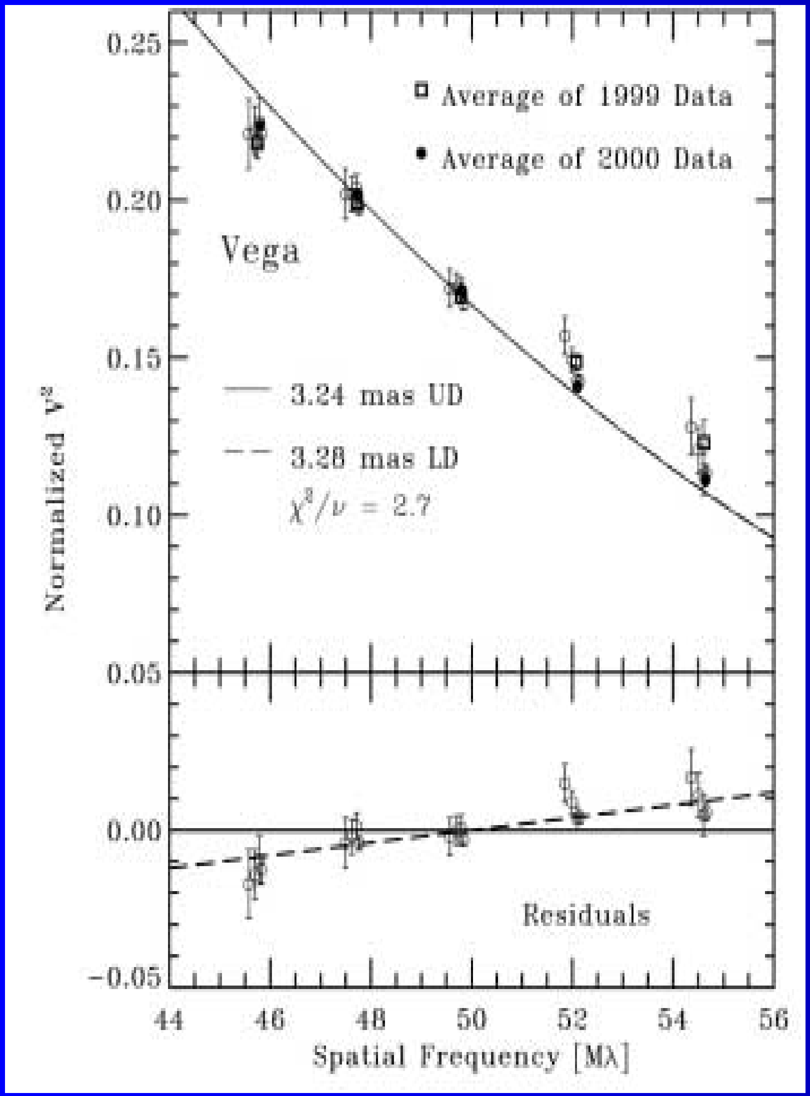
- T Tauri stars are solar-like pre-main sequence stars.
  - Surrounded by accretion disk
- SED modeling predicts much smaller inner radius than measured by PTI.
- SU Aur: same result

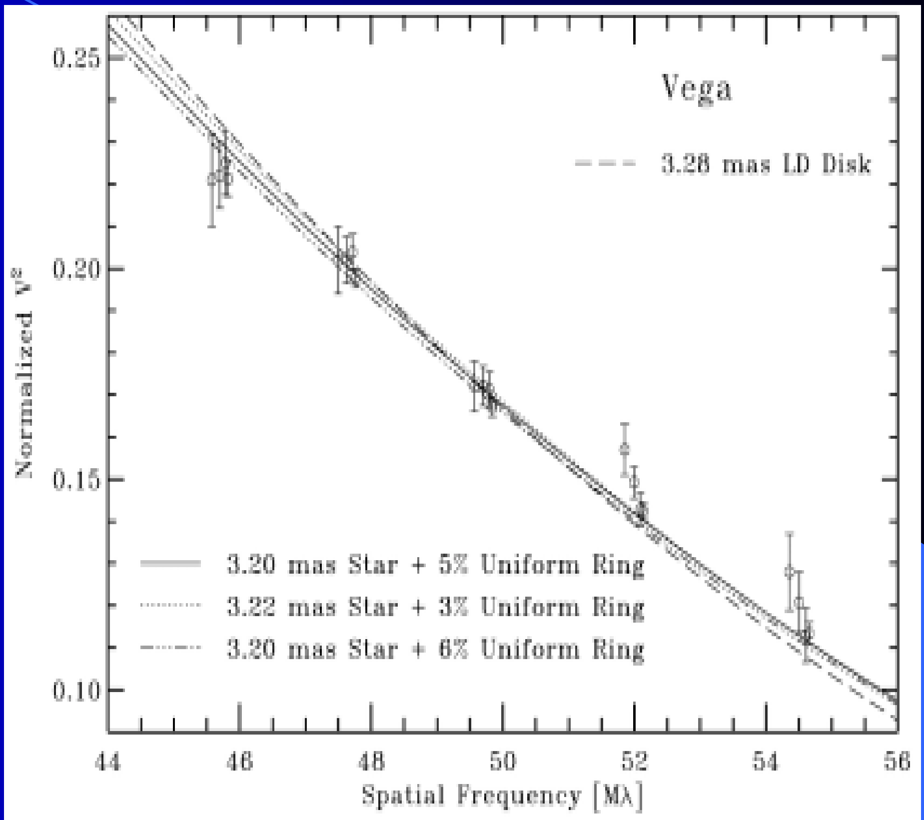


NIR SED Modeling
PTI V^2 Modeling
MM SED Modeling



Circumstellar Material II: Vega

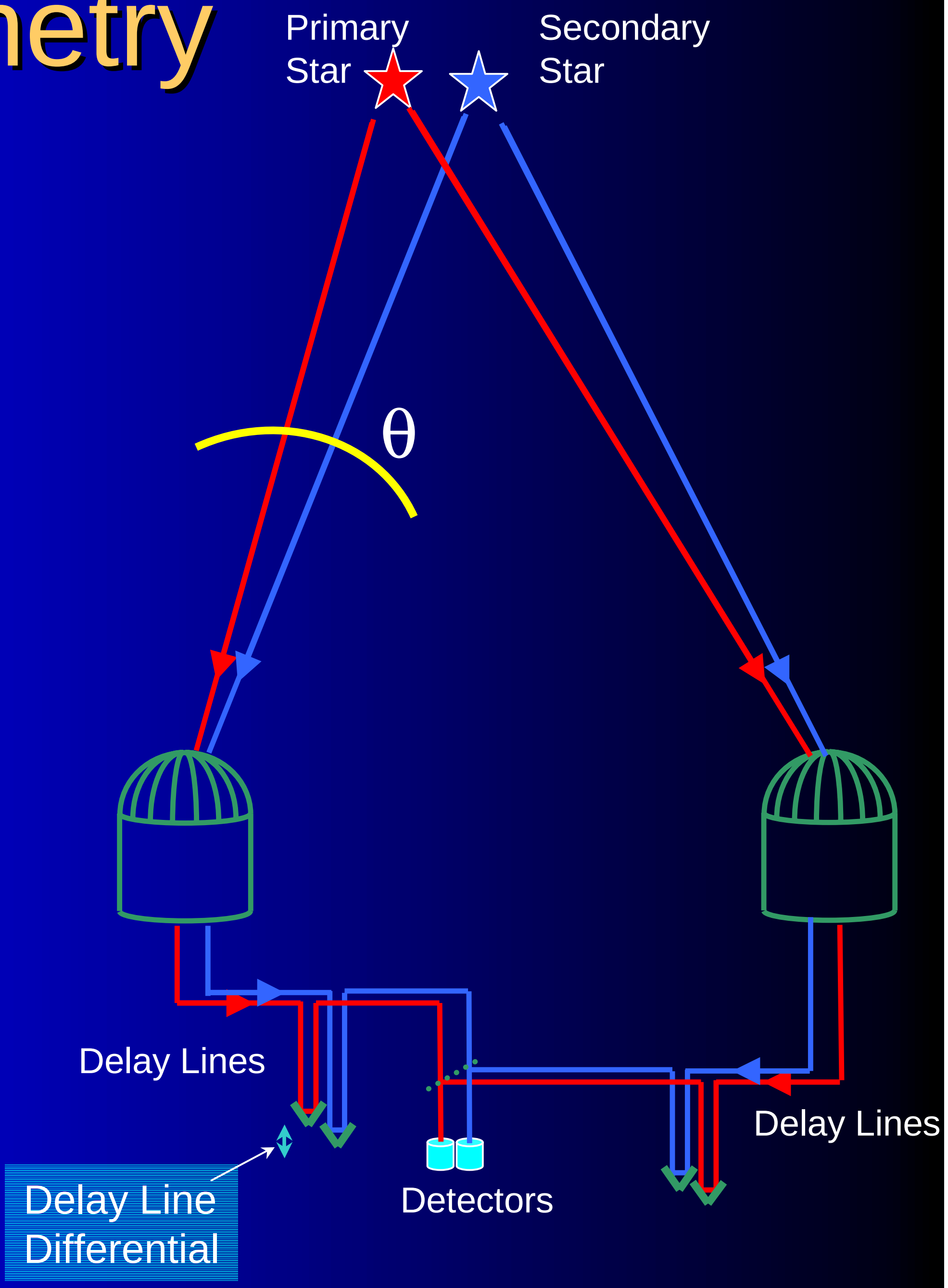




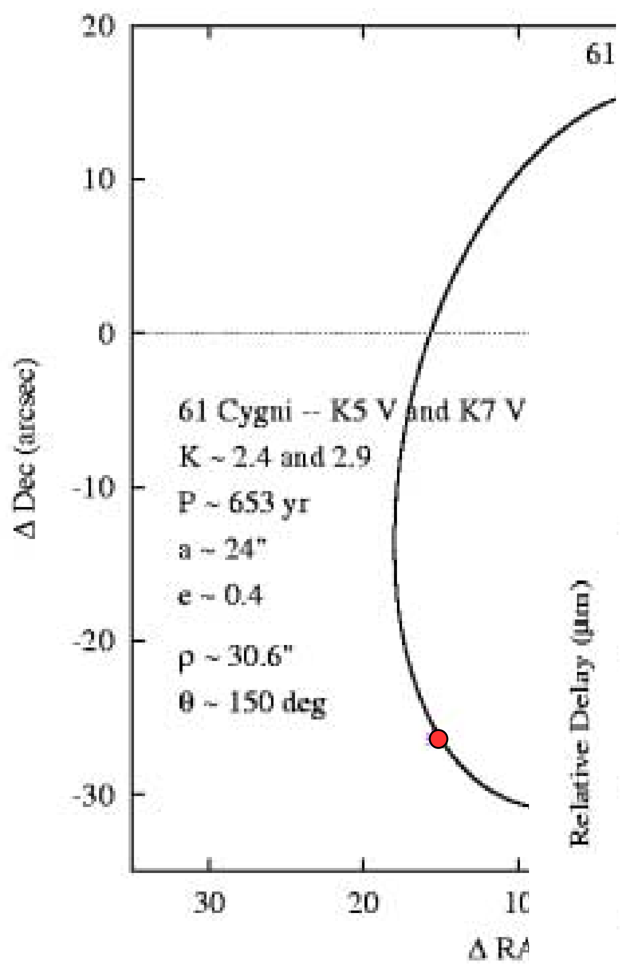
- Fit Vega with Stellar Disk.
- Unexplained residuals in fit.
- Added disk with 5% flux.
  - Appropriately corrects fitting.

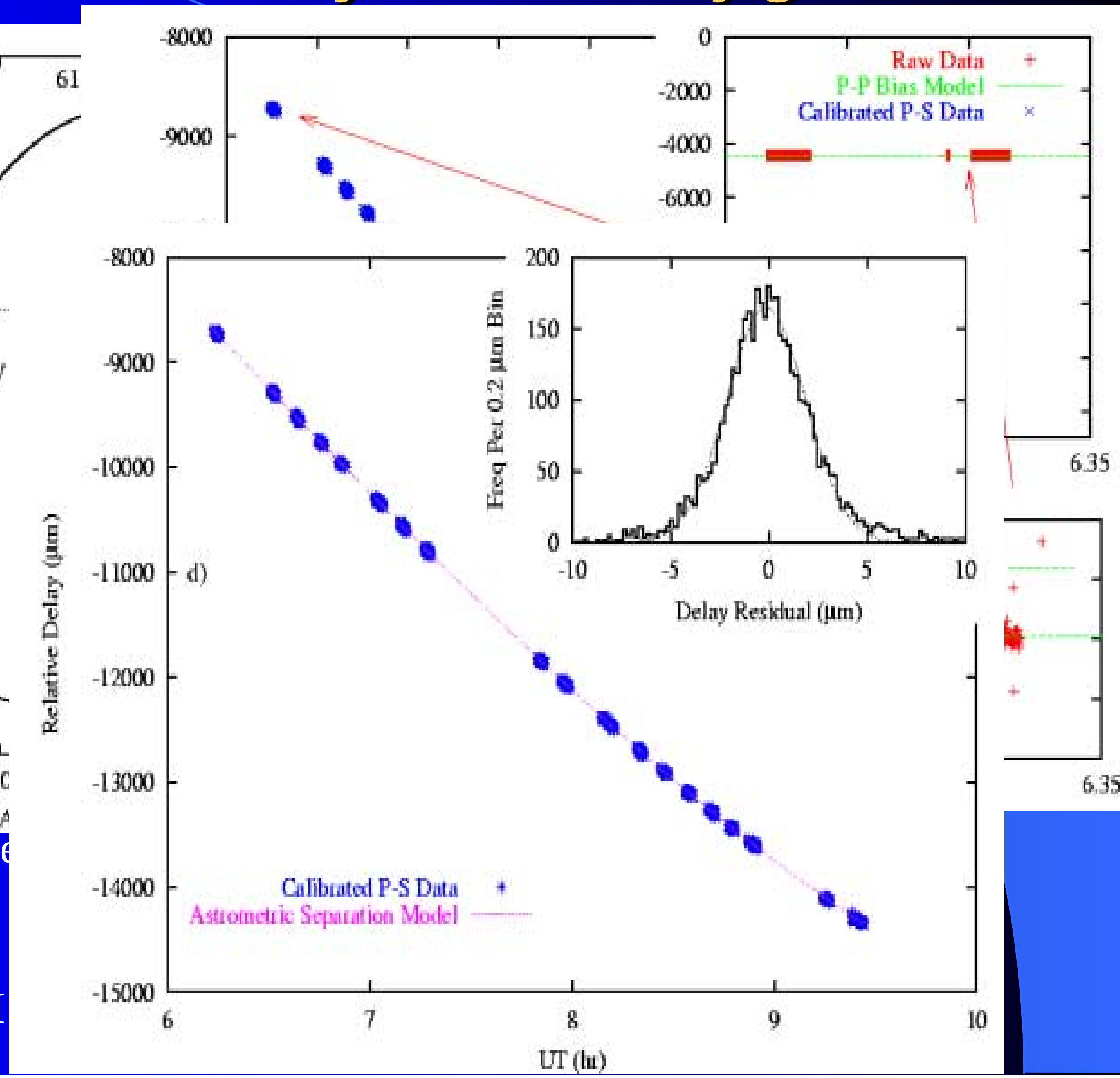
Dual Star Astrometry

- Primary star (target) - bright
  - Used to stabilize interferometer
- Secondary star - faint
  - Position reference
  - Located in same isoplanatic patch as primary star
  - Long integration times possible
- Delay line position difference
  - Proportional to angular separation between stars
  - Measured with laser metrology
  - Wobble in separation indicative of unseen companion



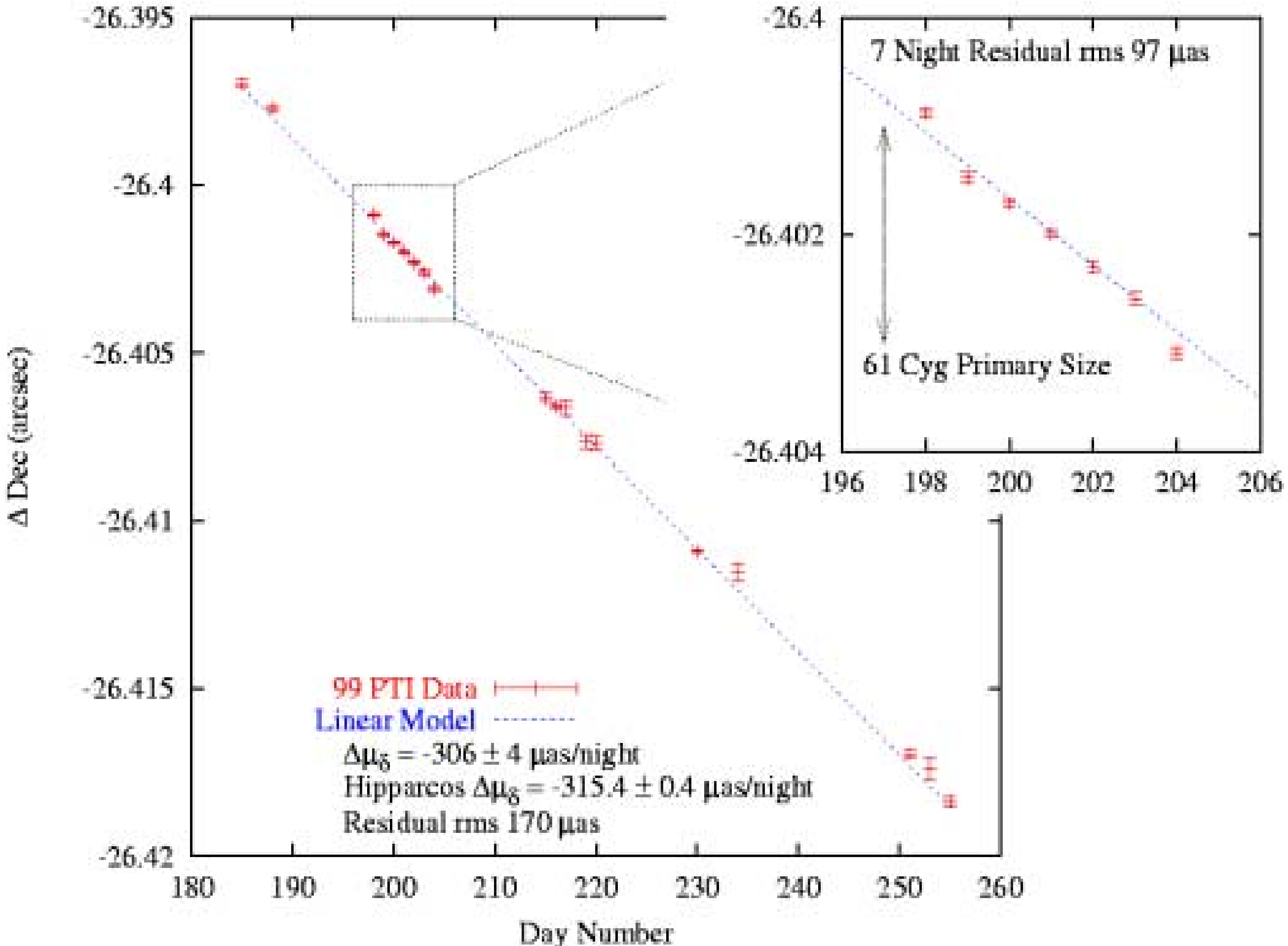
PTI Astrometry on 61 Cygni

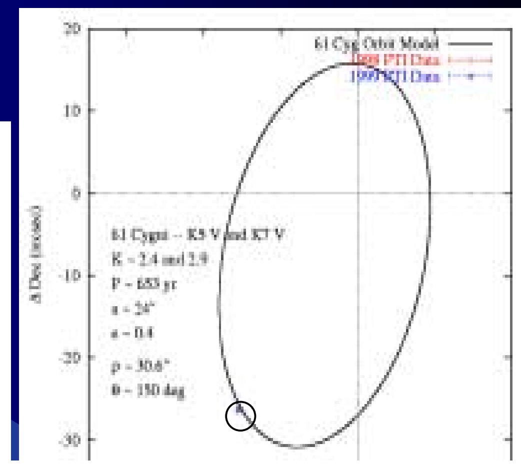


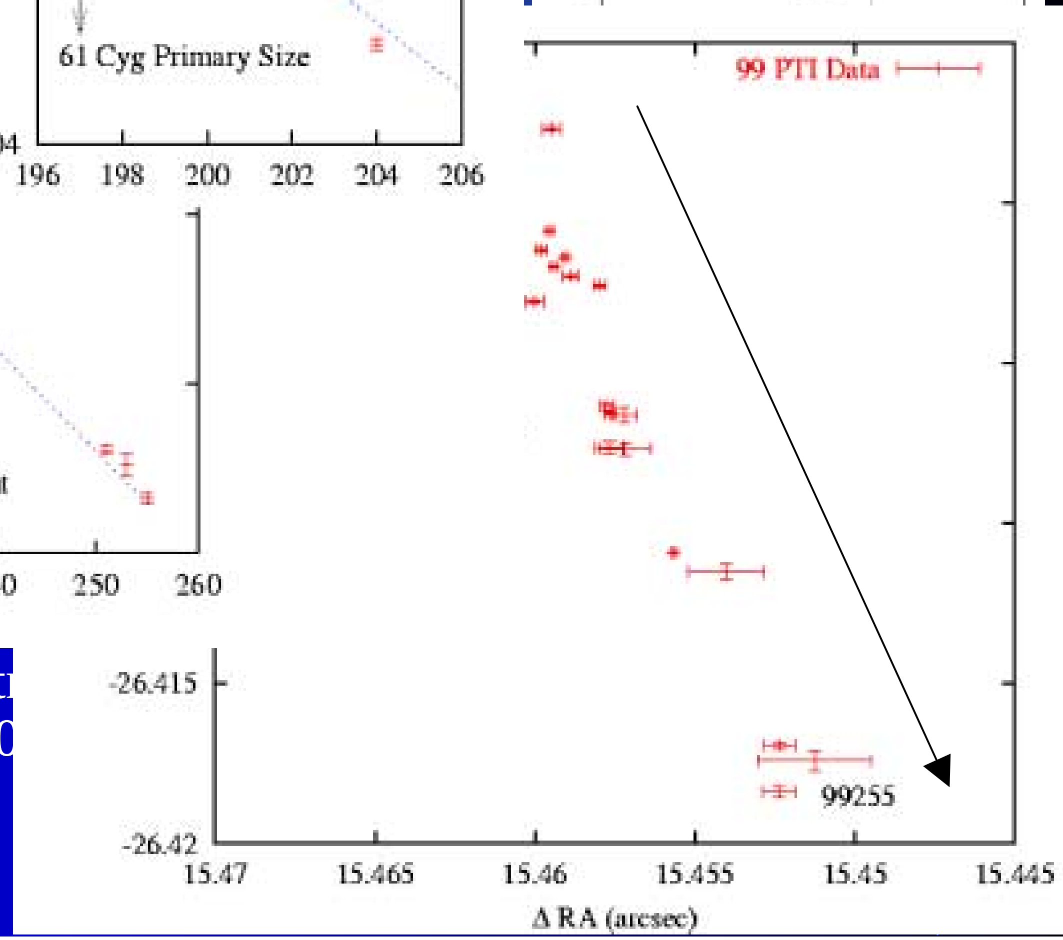


Objective: ground-base
astrometric detection
of exo-planets
~ 50 -- 200 µas @ PTI

PTI Astrometry on 61 Cyg (2)







Objective: ground-based astromet[...] detection of exo-planets ~ 50 -- 20[...] μas @ PTI

Dual-Object Phase Referencing

- Phase referenced interferometry: the analog of single-aperture AO
  - Fringe tracking piston correction signal on one object is used to correct the piston on a second, nearby (isoplanatic separation) object.
  - Required for KI (*and VLTI*) faint-object interferometry
  - Phase error with and without loop closed between the two PTI fringe trackers.
  - Two data segments taken within 200 s of each other.
- Objective: long synthetic coherence time for faint-object detection